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*WHITE LIGHT SCHLIEREN OPTICS USING BACTERIORHODOPSIN  
AS AN ADAPTIVE IMAGE GRID*

Dr. Robert E. Peale, Assistant Professor  
Mr. Boh Ruffin, Graduate Student  
Mr. Jeff Donahue, Undergraduate Student  
Physics Department  
University of Central Florida (Peale and Donahue)  
University of Michigan (Ruffin)

KSC Colleague - Carolyn Barrett  
Instrumentation and Hazardous Gas Monitoring

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## ABSTRACT

A schlieren apparatus using a bacteriorhodopsin film as an adaptive image grid with white light illumination is demonstrated for the first time. The time dependent spectral properties of the film are characterized. Potential applications include a single-ended schlieren system for leak detection.

## 1. INTRODUCTION

Remote imaging of leaks is needed at large industrial complexes including, for example, the space shuttle launch facilities at Kennedy Space Center. Backscatter/Absorption Gas Imaging (BAGI) [1] is useless for gases which lack strong IR absorption, such as O<sub>2</sub>, H<sub>2</sub>, He, and N<sub>2</sub>. This and other laser techniques, e.g. Raman imaging, may be dangerous for personnel and equipment. A system using white light, preferably ambient light, is desirable.

The schlieren method is well established for viewing plumes of foreign gases in air[2]. The test region is sandwiched between a source grid and its negative, onto which the source grid is imaged using appropriate optics. Only rays deflected by a plume in the test region may pass the image grid. These rays are used to image the plume. By thus eliminating the uninteresting background, the signal-to-noise is greatly enhanced, and otherwise invisible plumes appear in high-contrast detail.

All usual schlieren set-ups sandwich the test region between optics, which limit the field of view to industrially uninteresting scales. Peale and Summers[3] showed that the optics on one side can be replaced by a high contrast pattern on flexible reflecting cloth. A zoom lens images the pattern onto its negative. This scheme can be scaled to large fields of view with only modest cost increases, in principle. An obvious extension of this idea is to substitute a naturally occurring high contrast scene for the pattern-cloth combination, thereby creating a single-ended schlieren system. The negative can be photographic, but exposure, development, reinsertion, and realignment are time consuming operations, during which the scene and its illumination may change.

Erasable photochromic films offer an attractive alternative. Films of bacteriorhodopsin (BR) from the purple membrane of Halobacterium Halobium are promising because larger absorbance changes and more cycles can be achieved than with man-made photochromic chemicals[4]. In the simplest model, the BR ground state (bR state) has a strong absorption in the yellow-green. Absorption by this band pumps BR into its long-lived excited M-state, which absorbs in the blue. Thus, a negative of a scene in blue light can be created in a BR film using yellow-green light.

Downie has demonstrated a BR schlieren apparatus using blue and green laser light [5]. Use of white light and color filters was unsuccessful, however. We demonstrate successful white-light BR schlieren with performance only 2 times worse than a traditional schlieren apparatus. Our system is sufficiently sensitive to observe the heat waves generated by the human body. This result is a first step in realizing a truly single-ended remote imaging system for leaks using white

light. A variety of laboratory applications can also be envisioned.

## 2. EXPERIMENT

Transmission spectra were collected using a diverging incandescent source, a 400 to 700 nm variable interference filter having 20 nm bandwidth, and a large area photovoltaic detector. Low intensity measurements were performed with this set up by placing the BR film just in front of the detector where the beam spot size is about 2 cm. Here, no time dependence is observed in the transmission. Higher intensity measurements were performed by placing the film just after the interference filter where the spot size is still just a few mm, and strong time dependence is observed. Data were recorded on a strip chart recorder.

Time dependent transmission data were also recorded using a variety of blue-violet band pass filters, long pass filters, and a common flood lamp. This source and two of the filters were used subsequently for schlieren experiments. A large-area Si detector was used in photovoltaic mode with a variety of low impedance load resistors to maintain linear response. The output was recorded on a strip chart. Neutral density filters were moved from front to back of the BR film to provide a range of incident intensities at the BR film while keeping the average intensity at the detector constant.

Standard schlieren optics in the configuration shown in Fig. 2.1 collected images of a variety of phase objects for comparison with BR schlieren. The BR schlieren set up is shown schematically in Fig. 2.2. A ground glass plate diffused the flood lamp illumination and reduced UV emissions. The heat absorbing filter was Schott KG2. The long pass filter was Schott OG550. The blue-violet band pass was Schott BG12, which was combined with a neutral density filter having an optical density of 1. The 19-inch, six-foot focal length spherical mirror imaged the source grid either onto the image grid (Fig. 2.1) or onto the bacteriorhodopsin film (Fig. 2.2). The grid(s) were Ronchi ruling(s) having 50 lines per inch from Edmund Scientific. A Javelin JE2062IR black-and-white ccd camera monitored the test region, which was located just in front of the spherical mirror. A zoom lens optimally filled the camera image plane with the test region.

The bacteriorhodopsin film was obtained from Bend Research and had a nominal optical density of 2.8 at 570 nm (absorbance of 6.5). The wild-type BR was incased in polyvinyl alcohol to form a ~100  $\mu\text{m}$  film. The nominal M-state lifetime was 1 to 5 s.

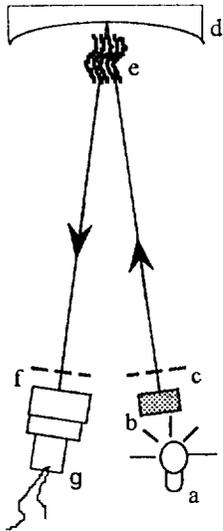


Fig. 2.1. Schematic of standard schlieren optics. a) Source; b) diffuser; c) source grid; d) spherical mirror; e) phase object; f) image grid; g) camera with zoom lens.

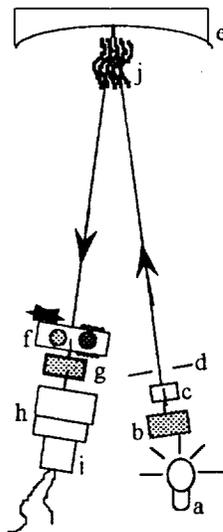


Fig. 2.2. Schematic of a bacteriorhodopsin schlieren set-up. a) Source; b) diffuser; c) heat-absorbing filter; d) source grid; e) spherical mirror; f) filter holder with two interchangeable filters; g) bacteriorhodopsin film; h) zoom lens; i) camera; j) phase object.

### 3. RESULTS

The relevant optical properties of our BR film were characterized first. Fig. 3.3 presents absorbance spectra. The solid circles were taken at an intensity sufficiently low that no time dependence of the transmission was observed. The cross symbols in Fig. 3.3 give the absorbance spectrum immediately after completion of a higher-intensity bleach transient using 525 nm light. Since BR has no absorption at  $1\ \mu\text{m}$ , the experimental absorbance at  $1\ \mu\text{m}$  was subtracted to eliminate contributions of reflection and scattering. After the bleach, the absorbance is everywhere lower except near 400 nm. The solid diamond symbols in Fig. 3.3 represent the difference in the two curves, which reveal the decreased absorbance in the yellow-green region and the increased absorption in the blue-violet. These changes result from the light induced population of the BR metastable M-state.

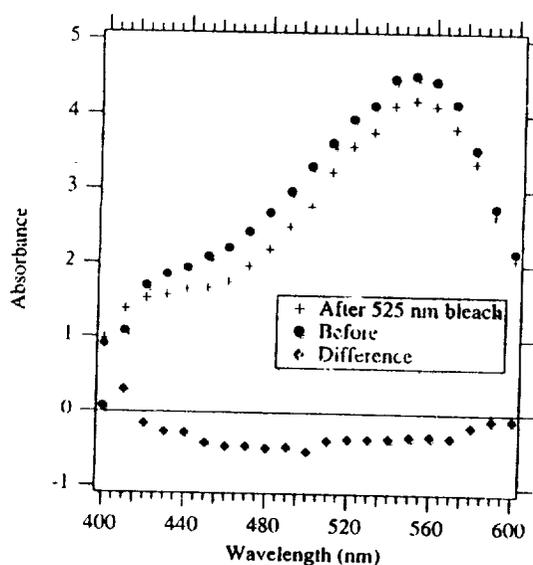


Fig. 3.3. Absorbance spectra before and after creation of M-state population in the bacteriorhodopsin film and their difference.

Fig. 3.4 shows the recovery dynamics of the bR-state absorption near 550 nm. The solid symbols show the absorbance normalized to its maximum value as a function of time spent in the dark after completion of a bleaching transient. A half life of about 10 s is observed for this recovery. The open symbols show the absorbance as a function of time spent under 450 nm illumination. These

data reveal the well known effect that wavelengths coincident with M-state absorption hasten M-state depopulation [4]. Since schlieren results are taken with blue light, Fig. 3.4 shows that the read light should be attenuated if long read times are required.

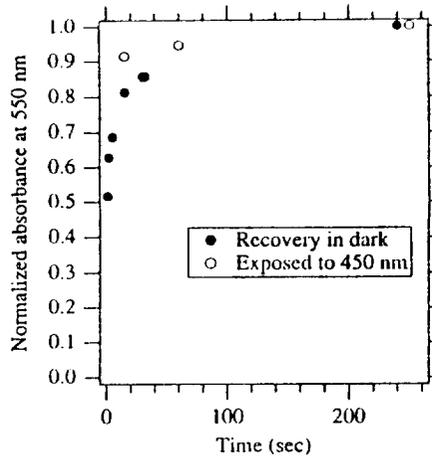


Fig. 3.4. Recovery dynamics of bacteriorhodopsin ground-state absorption in the dark and with blue illumination.

Fig. 3.5 compares the efficiency of different bleaching-wavelengths on the 400 nm absorbance change vs. intensity. Long-pass filters for writing and a 400 nm band-pass filter for reading were used. The shorter wavelengths included with the 475 nm long-pass filter result in a smaller change at 400 nm. These shorter wavelengths may be absorbed by the tail of the M-state absorption, thus helping to reduce its population.

Fig. 3.3 suggests that the largest absorbance increases occur at 400 nm or below. However, wavelengths below 400 nm should give only smaller changes[4]. This was tested using 550 nm long-pass filter and a number of blue-violet band pass filters. Fig. 3.6 presents the results, where the read wavelength is given for each solid symbol. The largest absorbance increases are confirmed to occur near 400 nm.

Figs. 3.5 and 3.6 reveal that the best filter combination for the schlieren experiments is the 550 nm long-pass for writing the image grid and the 400 nm band pass for reading it. The largest expected absorbance change at the read wavelength is about 1.3. An additional observation is the appearance of an optimum intensity well below the film's damage threshold. This phenomenon is unexplained by the simple two state model but is consistently observed.

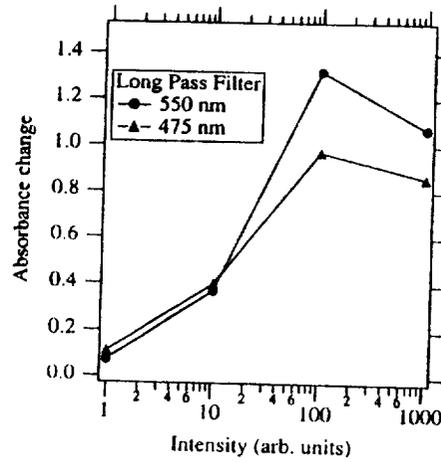


Fig. 3.5. Absorbance change at 400 nm as a function of intensity for different write filters.

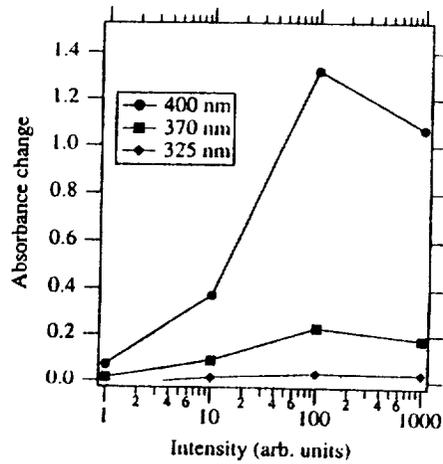


Fig. 3.6. Absorbance change at various read wavelengths as a function of intensity using a 550 nm long pass as the write filter.

Fig. 3.7 presents BR schlieren results for a low velocity flow of He gas. Turbulence is observed. Identifiable regions are darker on the left side and lighter on the right since schlieren is sensitive to index gradients which change sign when going across symmetric phase objects. For reprographic purposes, this image was processed with a ramp filter to enhance the contrast. Original digital data can be obtained by contacting the authors. In this experiment, a 1:1 image of the source grid was bleached into the BR film at an intensity sufficient to cause an absorbance change of 0.8 at 400 nm. The bleaching time was 10 s. The phase object was absent from the test region while writing the image grid. Then read filter and the phase object were simultaneously inserted, and an image of the test region was immediately recorded. Real time images of the test region were observed on a video monitor. While observing in the blue, the picture gradually brightened, and the contrast of the phase objects gradually faded to invisibility after several minutes. Then a reference image was collected.

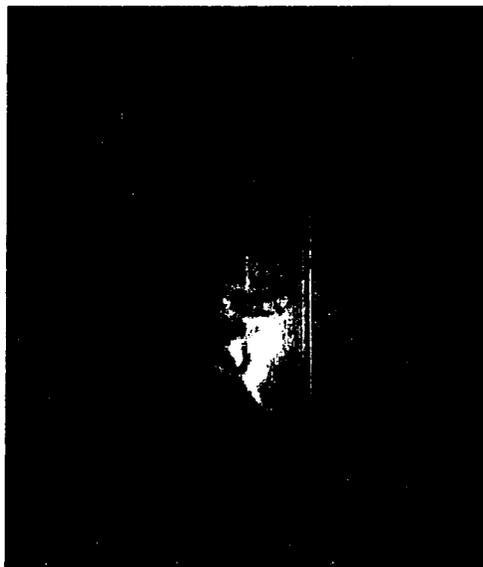


Fig. 3.7. Bacteriorhodopsin schlieren image of a low velocity He gas plume.

Fig. 3.8 presents an intensity profile across a portion of the unprocessed image taken immediately after the write procedure (lower heavy trace). It shows intensity variations of ~10% with spatial frequencies of a few tens of profile points. This is compared with a profile taken several minutes later (upper heavy trace). The long time profile reveals an overall increase in the transmission of the bacteriorhodopsin film and the nearly complete fading of the intensity variations that characterize the phase object. Also included is a profile taken with our standard schlieren set-up (faint trace). A strong slope to the baseline is observed because the phase object was located near

the edge of the field of view. The short period intensity variations are only about 2 times larger than the results obtained using BR. This suggests that BR schlieren can be as sensitive as standard schlieren but with the advantages of adaptability and automatic image-grid alignment.

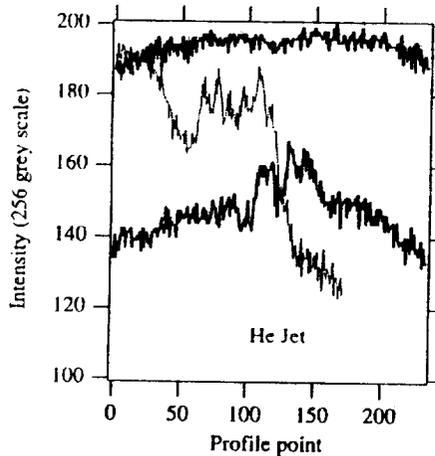


Fig. 3.8. Image profiles for the low velocity He plume. The thin curve is from standard schlieren results. Thick curves are from bacteriorhodopsin immediately after the write procedure (lower) and several minutes later (upper).

#### 4. SUMMARY

An adaptive schlieren apparatus using bacteriorhodopsin films as the medium for writing image grids has been demonstrated using white light as the illumination source for the first time. An image of a He gas plume revealed only 2 times less sensitivity than a standard schlieren apparatus.

#### 5. REFERENCES

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